

## REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 21-12-2010	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 1-Apr-2010 - 31-Dec-2010		
4. TITLE AND SUBTITLE Time Pressure Under Stress		5a. CONTRACT NUMBER W911NF-10-1-0063		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS hancock, kim		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Central Florida Office of Research University of Central Florida Orlando, FL		8. PERFORMING ORGANIZATION REPORT NUMBER		
32826 -0150				
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) 57985-LS-II.1		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited				
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
14. ABSTRACT People often fail to execute even a well-learned skill under stress and fatigue (e.g., time pressure). What are the necessary shortfalls in the cognitive mechanisms that govern this failure? To examine this failure, we consider that formalized modeling is one of the most logical and reasonable of all methods to help us refine and advance our understanding of real-world operational effects. Models force us to make our assumptions explicit and to expose the veracity or fallacy of those assumptions as experience is compared to prediction. Here, we examine the use of				
15. SUBJECT TERMS time pressure, stress				
16. SECURITY CLASSIFICATION OF: a. REPORT UU		17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Peter Hancock
				19b. TELEPHONE NUMBER 407-823-2310

## **Report Title**

Time Pressure Under Stress

### **ABSTRACT**

People often fail to execute even a well-learned skill under stress and fatigue (e.g., time pressure). What are the necessary shortfalls in the cognitive mechanisms that govern this failure? To examine this failure, we consider that formalized modeling is one of the most logical and reasonable of all methods to help us refine and advance our understanding of real-world operational effects. Models force us to make our assumptions explicit and to expose the veracity or fallacy of those assumptions as experience is compared to prediction. Here, we examine the use of the ACT-R architecture and the way in which it has been and can be employed to understand the often deleterious influences of stress and fatigue on operator performance. It is well established that both physiological and psychological sources of stress (e.g., heat, cold, workload, time pressure, etc.) as well as the precursors to fatigue (e.g., hours of work, work repetition, demand overload circadian phase, etc.) significantly moderate both physical and cognitive performance capacity. We report the state of present understanding as to (a) what stressors have to date been modeled using the ACT-R architecture, and (b) what theories and mechanisms can be identified by this work as moderating performance under such stressed and fatigued conditions. In examining the implications and limitations of this and similar applications we provide a roadmap to advance modeling and simulation of performance under all adverse operational circumstances.

---

### **List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:**

#### **(a) Papers published in peer-reviewed journals (N/A for none)**

**Number of Papers published in peer-reviewed journals:** 0.00

---

#### **(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)**

**Number of Papers published in non peer-reviewed journals:** 0.00

---

#### **(c) Presentations**

**Number of Presentations:** 0.00

---

#### **Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):** 0

---

#### **Peer-Reviewed Conference Proceeding publications (other than abstracts):**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):** 0

---

#### **(d) Manuscripts**

**Number of Manuscripts:** 1.00

---

### **Patents Submitted**

---

## Patents Awarded

### Awards

#### Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

#### Names of Post Doctorates

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
Jong Kim	1.00
<b>FTE Equivalent:</b>	<b>1.00</b>
<b>Total Number:</b>	<b>1</b>

#### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

#### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

#### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 0.00

---

**Names of Personnel receiving masters degrees**

NAME

Total Number:

**Names of personnel receiving PHDs**

NAME

Total Number:

**Names of other research staff**

NAME

PERCENT\_SUPPORTED

FTE Equivalent:

Total Number:

**Sub Contractors (DD882)**

**Inventions (DD882)**



**DEPARTMENT OF PSYCHOLOGY  
UNIVERSITY OF CENTRAL FLORIDA**

---

**Cognitive Modeling of Performance Response  
Capacity Under Time Pressure**

7 September 2010

Peter A. Hancock and Jong W. Kim

[phancock@mail.ucf.edu](mailto:phancock@mail.ucf.edu)  
[jwkim@mail.ucf.edu](mailto:jwkim@mail.ucf.edu)

Technical Report No. 2010-0907

---

MIT<sup>2</sup> (Minds In Technology & Machines in Thought) Lab.  
Department of Psychology  
University of Central Florida  
Orlando, FL 32816

www.peterhancock.ucf.edu

Phone +1 (407) 823-2310

Fax +1 (407) 882-1335

# Cognitive Modeling of Interactive Response Capacity Under Time Pressure

P.A. Hancock & J.W. Kim

[p Hancock@mail.ucf.edu](mailto:p Hancock@mail.ucf.edu), [jw kim@mail.ucf.edu](mailto:jw kim@mail.ucf.edu)

Department of Psychology  
University of Central Florida

7 September 2010

Technical Report No. 2010-0907

## Abstract

People often fail to execute even a well-learned skill under stress and fatigue (e.g., time pressure). What are the necessary shortfalls in the cognitive mechanisms that govern this failure? To examine this failure, we consider that formalized modeling is one of the most logical and reasonable of all methods to help us refine and advance our understanding of real-world operational effects. Models force us to make our assumptions explicit and to expose the veracity or fallacy of those assumptions as experience is compared to prediction. Here, we examine the use of the ACT-R architecture and the way in which it has been and can be employed to understand the often deleterious influences of stress and fatigue on operator performance. It is well established that both physiological and psychological sources of stress (e.g., heat, cold, workload, time pressure, etc.) as well as the precursors to fatigue (e.g., hours of work, work repetition, demand overload circadian phase, etc.) significantly moderate both physical and cognitive performance capacity. We report the state of present understanding as to (a) what stressors have to date been modeled using the ACT-R architecture, and (b) what theories and mechanisms can be identified by this work as moderating performance under such stressed and fatigued conditions. In examining the implications and limitations of this and similar applications we provide a roadmap to advance modeling and simulation of performance under all adverse operational circumstances.

*Keywords:* Stress, Time Pressure, Cognitive Architecture, ACT-R

## Acknowledgements

Elmar Schmeisser provided several types of support for this work. Frank Ritter has helped our thinking in the cognitive modeling. The ACT-R community provides a background for this work. This project is supported by the Army Research Office, award number W911NF1010063.

## Table of Contents

Abstract.....	2
1 Introduction.....	4
2 Brief Overview of ACT-R .....	5
3 Performance Capacity Changes under Stress.....	6
3.1 Skill Execution: Declarative vs. Procedural .....	7
3.2 Task Skill Ontology.....	8
3.3 Modeling Stressors.....	10
3.4 Estimation of Time in ACT-R .....	10
4 Theories for Performance under Stress .....	11
4.1 Consideration of Attentional Capacity .....	11
4.2 Consideration of Interactive Behavior under Time Stress.....	14
4.3 Consideration of Working Memory Capacity.....	15
5 Summary for the Roadmap .....	15
5.1 Roadmap 1: Create an Advanced Study Paradigm for Modeling.....	16
5.2 Roadmap 2: Develop Cognitive Models.....	17
5.3 Roadmap 3: Embody the Cognitive Model .....	17
5.4 Further Challenge: Identify the Three Stages.....	18
References.....	19

# 1 Introduction

Sources of stress (e.g., heat, workload, fatigue, etc.) are well known to significantly moderate the human performance capacity (Hancock & Szalma, 2008). These stresses are often limited to particular operational environments. In contrast, time pressure is a ubiquitous source of stress. An individual (from a beginner to a skilled expert) performing under a time-constrained environment exhibits a variety of forms of systematic failure.

What are the necessary shortfalls in the cognitive mechanisms that govern this failure? It is very important to understand such cognitive mechanisms because they can be utilized to construct a formal model to provide predictions of behavior in advance operational conditions. There is relatively little research about failed execution of task skill especially under time stress.

For example, individuals under time stress frequently fall prey to an omission of one step in a procedural sequence even when that sequence is a relatively well-learned one. This error, or lapse, can be considered as a form of memory failure (Reason, 1997). Such lapses are ubiquitous across various forms of tasks in both the civilian and military worlds.

While on many occasions the occurrence of such events provides no critical outcome, such lapses do represent significant opportunities for tragedy to occur. That is, individuals in many forms of emergency response or extremely high workload conditions, especially life-threatening combat operations, encounter time-stressed decision-making requirements almost continually in their occupational pursuits. Although these are particularly evident instances, time stress is found on many occasions in most forms of human performance. The issue of memorial lapses already mentioned is only one form of potential time-induced failure.

## A Research Paradigm: Cognitive Model in a Unified Theory of Cognition

The ultimate objective of our research study is to provide a unified cognitive theory of stress that can be implemented in a cognitive architecture by providing a formal model with more accurate behavior prediction under stress and fatigue. To achieve this objective, we will use a formalized cognitive architecture. This is because a cognitive architecture has been developed to provide *complete processing models* (Newell, 1973). Rather than an isolated or divided subfield in cognitive psychology, a cognitive architecture is an implementation of unified theories of cognition (see Newell, 1990), providing a methodology through which to model the richness of the whole spectrum of human operator performance.

Perhaps, the most widely used cognitive architecture is ACT-R, *Adaptive Control of Thought—Rational* (see Anderson, 2007a; Anderson et al., 2004; Anderson & Lebiere, 1998). ACT-R supports a wide range of empirical phenomena in cognitive psychology including memory, learning, problem-solving, and perception/action response. It has also been employed in other Army applications (e.g., Lebiere et al., 2002). However, most cognitive architectures including ACT-R have not been developed with theories of stress and fatigue in mind. Thus, it is important to explore how theories of cognition and stress may be unified in this or any other cognitive architecture. Here, we identify and examine some example research studies that have begun to address stress and fatigue effects in ACT-R (e.g., Gunzelmann, Gross, Gluck, & Dinges, 2009) and the techniques to incorporate such theories of stress into a cognitive architecture (e.g., overlay, Ritter, Reifers, Klein, & Schoelles, 2007).

Based upon our work, we have found that there are various theories of stress but unfortunately those theories are incomplete, not making predictions consistent with known human performance data (Ritter, Reifers, Klein, & Schoelles, 2007). In particular, there is little research providing a unified theory of cognition under time stress (Kim & Hancock, 2010). Thus, it is very necessary to answer the ultimate question of what mechanisms govern the failure of a learned skill under stress, particularly time stress. As an interim report, we enumerate the important theoretical foundations and corresponding roadmap for our pursuit.

## 2 Brief Overview of ACT-R

Architecture can indicate designing something out of physical components. The components in a building architecture can include walls, floors, windows, or foundation. With this analogy, a computer architecture was introduced to computer science and then a cognitive architecture was also introduced to cognitive science. John Anderson (2007a) defined a cognitive architecture as:

Cognitive architecture is a specification of the structure of the brain at a level of abstraction that explains how it achieves the function of the mind. (pp. 7)

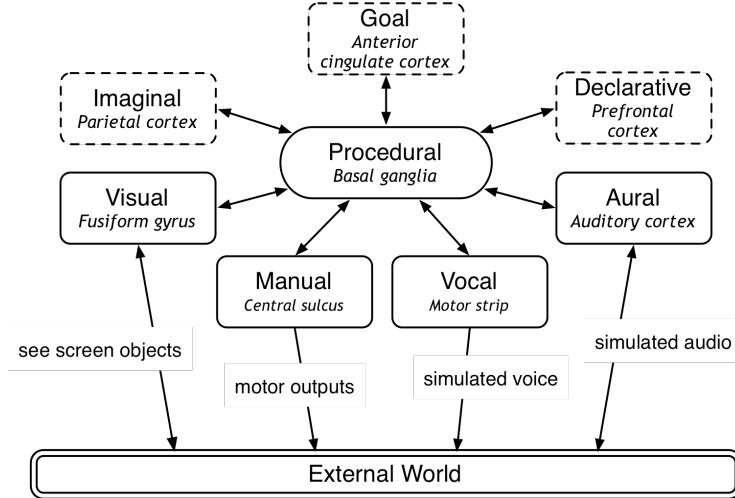
In John Anderson's definition, two important terms are recognized: the structure of the brain and the function of the mind that can be referred to cognitive performance. Anderson (2007a) states that researchers often get lost in infinite details of the brain structure (e.g., a pyramid of neurons) and also get lost in infinite details of the function of the brain, arguing that we need an abstraction that links an understanding between the structure and the function of the brain. Cognitive architecture reflects this abstraction to better understand and model the human mind.

Gray (2008) provides a taxonomic analysis of various cognitive architectures and their use in human factors and cognitive engineering. A cognitive architecture as a unified theory of cognition (see Newell, 1990) combines multiple memory systems and embodied cognition to produce human behavior.

ACT-R is a hybrid cognitive architecture containing symbolic and subsymbolic constructs and relies on a modular organization to represent the brain's functional constraints in local regions (Anderson, 2007a, 2007b; Anderson et al., 2004; Anderson & Lebiere, 1998). Anderson (2007a) describes the symbolic level in ACT-R as an abstract characterization of how brain structures encode and process knowledge and the subsymbolic level as an abstract characterization of the role of neural computation in making that knowledge available. ACT-R basically consists of eight modules that are mapped onto brain regions. Figure 1 shows a schematic representation of the ACT-R architecture and the modules that correspond to each brain region.

As shown in Figure 1, the ACT-R architecture consists of several core modules. The procedural module plays a central role in coordinating productions that interact with other modules. This module specifies productions and matches a production to fire. The declarative module retrieves and stores an item, called a chunk. The goal module produces goal-directed behavior, tracking the current state of a model and holding relevant information for the current task. The only action of the goal module is to create new chunks, and they are placed into the goal buffer. The imaginal module creates new chunks that are the model's internal representation of new information, maintaining context that is relevant to the current task. The other four modules—the visual and aural modules address stimuli from the environment, and the manual and vocal modules produce outputs of hands and voice to the world—provide a way to interact with an environment.

With this modular characteristic of ACT-R, one can extend the architecture by adding a module to it, such as a spacing module representing the spacing effect of practice (see Pavlik & Anderson, 2005) and a timing module representing the passage of time (see Taatgen, van Rijn, & Anderson, 2007).



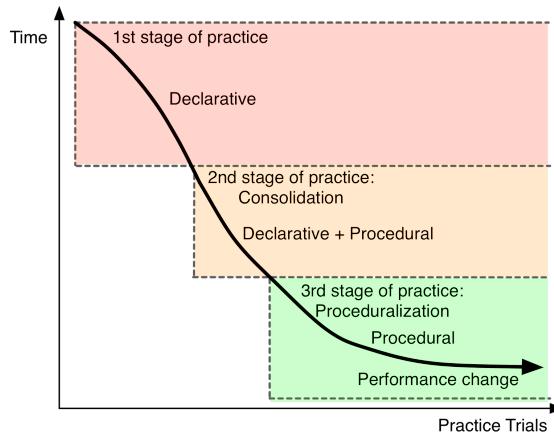
*Figure 1.* An overview of the ACT-R architecture. Solid single line boxes are modules that interact with the world (external) and dashed line boxes are internal modules. The hypothesized corresponding brain regions for each module are italicized.

### 3 Performance Capacity Changes under Stress

Individuals from beginner, through intermediate, to skilled individuals all suffer from degradation of successful skill execution under stress and fatigue. For a skilled individual, a failure to execute a well-practiced skill can be described by the term, *choking*, which indicates poor performance than expected given one's level of experience—*choking* is typically observed in sport as below expected level performance. These are special examples but failure of execution under stress can be observed across many domains. Particularly, we are interested in time pressure as a stressor that moderates performance. Time pressure is, perhaps, the most prevalent form of stress in the world of modern operations. An individual performing under time pressure exhibits a variety of forms of systematic failure. For example, individuals in many forms of emergency response or extremely high workload conditions, especially life-threatening combat operations, encounter time-stressed decision-making requirements almost continually in their occupational pursuits.

Task skill is typically learned in the three stages: (a) the first stage to acquire declarative and procedural knowledge, (b) the second stage for consolidating the acquired knowledge, and (c) the final stage for tuning the knowledge toward overlearning (e.g., Anderson, 1982, 1987). As the task skill is practiced (following the curve from the left to the right in three stages shown in Figure 2), it can be assumed that attentional resources would be reduced in executing the task skill. In the early stages, more attentional resources are required to execute the skill. On the other hand, in the later stage (i.e., the third stage), the task skill can be executed without excessive effort as related to attentional resources. Performance capacity is changed when it comes to these differing stages and also as a stress.

What governs this performance change under stress? Is it because attentional focus is shifted to task-irrelevant cues (e.g., Easterbrook, 1959; Wine, 1971)? Is it because there is increase in attention that is being paid to step-by-step execution of the task skill set rather than the proceduralized skill set in the later stage of learning (e.g., Baumeister, 1984; Lewis & Linder, 1997)? There are various cognitive accounts under stress but some accounts take an opposite position to others. Unfortunately, none of cognitive theories of stress are complete enough to build a formalized model that predicts moderated behavior. Thus, it is very useful to have a unified theory of cognition that represents human behavior under stress and fatigue.



*Figure 2.* Skill execution in the stages with declarative, procedural, and mixed representation of knowledge. Performance response changes (i.e., decrease in task completion time over trials) across the three stages.

### 3.1 Skill Execution: Declarative vs. Procedural

Execution of any task skill relies on certain learned characteristics (i.e., declarative, declarative + procedural, and procedural capacities) in each stage of learning (see Figure 2). In the earlier stage, the task skill that is based on fact retrieval in working memory can be vulnerable to forgetting. In the later stage, execution of the task skill more relies on proceduralized knowledge and skills. A fundamental understanding of the stress factor and these three stages of performance capacity is required to predict performance degradation under stress—how time pressure affects performance in terms of the three stages of performance capacity change shown in Figure 2.

To illustrate our case, we present a simple example of learning typing skills (e.g., Anderson, 1993). While common, learning typing skill has the same structure as many similar skills where declarative knowledge leads to procedural knowledge. This example can help us to better understand the distinction of memory between declarative/procedural knowledge and the three stages of learning.

When learning to type, the individual generally first memorizes the layout of the keyboard declaratively and learns to use the keyboard procedurally through sequential practice. Practicing typing skills enables the individual to memorize the keyboard layout and to type faster with practice. Over time (several months or more), the individual generally loses their declarative knowledge of the keyboard's layout but retains their procedural typing skills. Thus, once fully learned, few participants determine any key position declaratively (e.g., imagining typing a letter and seeing where their finger goes), but rather rely exclusively on their proceduralized knowledge of the task.

This example illustrates how individuals can and do maintain both declarative and procedural knowledge in memory, and how the kinds of memory utilized can be both dependent and independent at different stages. In addition, it suggests that procedural knowledge can be more robust. In the first stage, the individual depends almost exclusively on declarative memory elements to perform the task—this initial stage is both cognitively intensive and slow. In the second stage, the individual begins to rely more heavily upon procedural memory elements, but for some “problem” keys still relies on their declarative knowledge of the keyboard (*q* is above *a* for instance). Finally, as the individual evolves into an expert, they shift entirely or almost entirely to utilizing their procedural memory. In addition, the transition from a primarily declarative to a procedural representation of the keyboard is associated with a reduced need for knowledge maintenance—lack of practice may result in slower typing speeds but not an entire loss of the skill.

Early experimental work by Posner (1973) showed that procedural memory is more robust. In Posner’s experiment, skilled typists were asked to label a diagram of a standard keyboard. He reported that the skilled typists had difficulty in recalling a visual location of a letter from the standard keyboard (declarative memory), whereas the typists could type the letters in a few seconds without errors. This example supports declarative knowledge of visual location can be degraded while procedural knowledge can remain robust against decay, suggesting that long-term retention can be possible when declarative knowledge turns into procedural knowledge.

Among the numerous findings concerning memory and learning, there is a consensus understanding on skill acquisition represented in the three stages (e.g., Anderson, 1982; Fitts, 1964; VanLehn, 1996). All of these stages explain how skills are acquired and executed in a stable manner as experience increases, but unfortunately failing under the driving stress of time pressure remains unexplained. Figure 2 shows the stages in which a skill is learned. As practice increases, the task completion time decreases. This learning behavior is explained by an activation mechanism and a production compilation in the ACT-R theory.

In general, in the first stage (declarative stage), individuals learn knowledge and skills from instructions. Acquiring information is first supported through initial encoding of facts about the skill. Then, in the second stage (declarative + procedural), acquired task knowledge is interpreted to produce behavior. Through a mechanism called knowledge compilation (e.g., Anderson, 1982; Anderson & Lebiere, 1998; Neves & Anderson, 1981), the acquired knowledge is converted to a procedural form with appropriate practice. This knowledge compilation is called chunking in Soar and proceduralization in other theories. After knowledge compilation, further tuning of the knowledge occurs in the third stage, producing speedup of the knowledge application process, which is referred to as the procedural stage. This learning behavior generally follows a regularity known as the Power law of learning, explaining that the time to complete a task speeds up with practice but the amount of improvement decreases as practice continues (e.g., Anderson, 1983; Card, English, & Burr, 1978; Delaney, Reder, Staszewski, & Ritter, 1998; Newell & Rosenbloom, 1981; Ritter & Schooler, 2001; Seibel, 1963).

## 3.2 Task Skill Ontology

Tasks are themselves stressors (Hancock & Warm, 1989). More specifically, different task skills can play an important role in different performance capacity changes under stress. Table 1 shows a task skill ontology, which is inspired by the modular representations of the ACT-R architecture. Recently, Anderson (2007a) presented persuasive evidence that the ACT-R modules map onto human brain regions—the procedural module maps onto basal ganglia, the declarative module maps onto prefrontal cortex, the goal module maps onto anterior cingulated cortex, the visual module maps onto fusiform gyrus, and the manual module maps

onto central sulcus. It is important to provide biologically plausible task skills classifications to generate a fundamental understanding of performance change under stress.

Table 1. *A task skill ontology based on ACT-R.*

Task Skill	Attributes	Examples
Procedural	Retrieve knowledge from memory	Assembly/disassembly,
	Produce behavior	Extraction of landmines,
	Make decisions	Coping with engine fires during flights (if well practiced)
	Combine and evaluate incoming or acquired information	Problem solving in mathematics
	Make decisions	Coping with engine fires during flights (choosing actions)
Perceptual	Recognize visual information	Visual search or detection
Motor	Execute motor outputs	Moving a mouse Pressing a key
Perceptual-motor (Perceptual-enactive)	Perceive visual information Execute motor outputs	Visual search or detection, Tracking
Speech	Produce vocal outputs	Speaking language
Listening	Process auditory information	Listening and comprehending language
Declarative (Information retrieval)	Recall declarative information from memory	Retrieving facts Language learning Coping with engine fires during flights (if not well practiced, retrieving actions)

A strong avenue for modeling performance capacity change can be opened by comparing the three different stages shown in Figure 2 to task skill ontology shown in Table 1. Unfortunately, there do not appear to be any extant studies comparing different task skill components when it comes to the three stages and under a stressful environment (e.g., time pressure). Such a study would be greatly help to provide a fundamental understanding execution of task skills under stress. It is our interests to pursue this opportunity in the present project.

The ACT-R architecture helps us to provide a scientific framework for the ontology. At the same time, the current ontology in Table 1 reveals what may be missing in the ACT-R theory and raises important items for improving architectural theories and mechanisms. One item is to further explain cognitive models of subtask skills acquisition (i.e., perception, motor, speech, or listening).

Can we tell which stage of learning the individual currently occupies? The ACT-R theory provides examples of learning passing through these stages, but no studies on procedural skill performance (i.e., retention) have been reported. Theoretically, these transitions are clear in Figure 1. Practically, there are and will be difficulties in measuring such transitions. There are at least two difficulties. One difficulty is knowing which stage the individual is in for a particular subtask; the second difficulty is that the complex tasks will have multiple subtasks, and managing this information and recognizing that the individual may be at different stages in subtasks has been problematic for human and computer tutors in the past.

### 3.3 Modeling Stressors

As one way to model stress in a cognitive architecture, a technique called an overlay has been used. This is a technique to include a theory of stress affecting cognition across all models within a cognitive architecture (Ritter, Reifers, Klein, & Schoelles, 2007). An overlay can be described as a set of adjustments of parameters in some operational mechanisms or mechanisms that directly modify parameters to reflect changes due to stress and fatigue.

For example, there have been several attempts to model stress and fatigue in a cognitive architecture. One of the very earliest was that of Jongman (1998) who attempted to model mental fatigue using the spreading activation mechanism in ACT-R. As a more developed work on modeling fatigue, the integration of biomathematical models into parameters in a cognitive architecture seemed to allow a cognitive model to account how fatigue from sleep deprivation impacts cognition (Gunzelmann, Gross, Gluck, & Dinges, 2009). Other studies have included modeling stress from time pressure (Lerch, Gonzalez, & Lebriere, 1999) and serial subtraction (Ritter, Schoelles, Klein, & Kase, 2007). These studies provide examples of the use of overlay in a cognitive architecture. Table 1 shows a summary of examples concerning stress and fatigue modeling in ACT-R.

In ACT-R related prior studies, it has been reported that a parameter that is used in the process of selecting a production rule is related to *arousal* or *motivation* (e.g., Belavkin, 2001; Jongman, 1998). Gunzelmann et al. (2009) also utilized the ACT-R utility mechanism to model decreased alertness. This approach suggests that it is worth exploring the utility mechanism to model time pressure effects on response capacity; a strategy that we seek to pursue. The reason is because the selection process of a production rule is controlled by calculating an expected utility,  $U_i(n)$ , for each candidate production rule.

Table 2. *A summary of previous studies on stress/fatigue modeling in ACT-R*

Reference	Stress/Fatigue	Task	Technique
Jongman, 1998	Mental fatigue	Memory task	Overlay
Lerch et al. 1999	Time pressure	Resource management	Overlay
Ritter et al. 2007	Stress	Serial subtraction	Overlay
Gunzelmann et al. 2009	Sleep deprivation	Psychomotor vigilance	Overlay

However, it is at present not understood nor conceptualized directly how time pressure can be modeled in the ACT-R architecture to represent changes of operators' performance response. For example, time pressure could influence retrieval of a goal from the goal module, and/or motor output in the manual module, and/or memory item retrieval in the declarative module. Thus, here, we explore the ACT-R theory to provide a potential and theoretical understanding of time pressure effects on performance.

### 3.4 Estimation of Time in ACT-R

In cognitive modeling, the perception of time is an important ability that can help explain a number of variations in human response. In general, time interval estimation has been grounded on two theories: (a) the *internal clock theory* and (b) the *attentional gate theory* (and see Block, Hancock, & Zakay, in submission). Based on these respective theories, there are a number of formalized models and the two cited models can be differentiated by the presence or absence of the direct attentional gate.

In the ACT-R architecture, the passage of time can be estimated by a timing module that has been recently incorporated in the overall architecture (Taatgen, van Rijn, & Anderson, 2007). This timing module is based on the former, pacemaker-based internal clock model (see Hancock, 1993). The central pacemaker generates pulses at certain frequencies and an accumulator counts these pulses. The basic assumption has traditionally been that the pacemaker generates pulses at a constant rate (although certain forms of stress and neurophysiological disturbance can affect pulse frequency). However, unlike this constant frequency assumption, the ACT-R timing module introduced by Taatgen et al. increases the interval between the pulses as the interval progresses. This timing module can run independently of other cognitive processes. One potential weakness in Taatgen's approach is that the representation of the longer time intervals may not be precise because time between pulses gets longer, although short time intervals would be accurate.

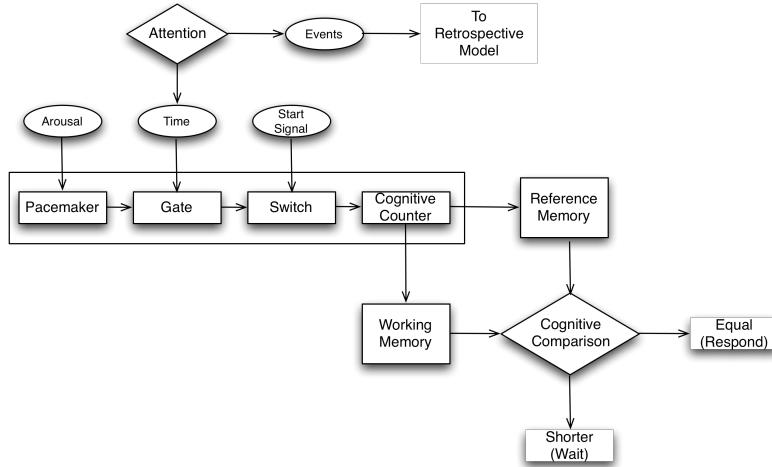


Figure 3. The attentional gate model of prospective time estimation (after Zakay & Block, 1997).

However, Byrne (2006) raised issues regarding the aforementioned timing module by Taatgen, van Rijn, and Anderson (2007). One issue is that timing of multiple overlapping intervals would be necessarily present in modeling time-sensitive complex tasks. The Taatgen's timing module utilizes non-uniform interval rates, making modeling efforts significantly harder than a constant frequency model. The other issue is that people generally underestimate intervals in most conditions (see Hancock & Rausch, 2010). Byrne argues correctly that the Taatgen's timing module would produce overestimation at the start of the time interval. Based on the alternative, attentional gate model (see Zakay & Block, 1997), Byrne has proposed a different timing module. The pacemaker in this model utilizes a fixed mean pulse rate so that a modeler can easily handle overlapping intervals by subtraction. Through the attentional gate model shown in Figure 3, pulses are registered or periodically missed. That is, pulses that are missed produce underestimation of timing. Moreover, this attentional gate models allows prediction of increased underestimation in terms of cognitive load (and see Block, Hancock, & Zakay, in submission). In contrast, Taatgen's module predicts no effect of cognitive load.

## 4 Theories for Performance under Stress

### 4.1 Consideration of Attentional Capacity

Attention is an important factor in almost all theories of stress. As mentioned earlier, the three stages where performance capacity changes occur require different attentional resources. That is, in the earlier stage, if

the task skill execution depends on retrieval of memory items in declarative memory, a stress factor would create the potential distraction to shift attentional focus to task-irrelevant cues such as worries, a process known as *distraction theories*.

In the early stage, performance change by distraction theories can be represented as the strength (or probability) of retrieval in declarative memory. This is formalized as the activation mechanism in the subsymbolic level of the ACT-R architecture. The ability to retrieve an item in declarative memory is associated with the activation equation, consisting of the base level activation ( $B_i$ ) and a noise component ( $\varepsilon$ ).

$$A_i = B_i + \varepsilon \quad \text{Equation 1.}$$

The base level activation for a chunk  $i$  is represented as:

$$B_i = \beta + \ln\left(\sum_{j=1}^n t_j^{-d}\right) \quad \text{Equation 2.}$$

$\beta$ : a constant

$n$ : the number of presentations for a chunk  $i$

$t_j$ : the time since the  $j$ th presentation

$d$ : the decay parameter

In ACT-R, the base-level activation is dependent on how often (frequency) and how recently (recency) a chunk is used. Whenever a chunk is presented, the base-level activation increases, and then decreases as a power function of the time. The time to complete a task (e.g., latency) appears to decrease as a power function of the number of trials of practice (see Anderson, Fincham, & Douglass, 1999).

Another relevant theory applies to explicit monitoring of task skill execution. In the middle and later stages, task skills are proceduralized, indicating execution of task skill is largely unattended without the service of working memory, like the skilled typist. This behavior is represented as knowledge compilation mechanism (Anderson, 1982, 1987). In this explicit monitoring theory, a stress factor raises anxiety about performing correctly, which causes the reversion of attentional focus to step-by-step control of skill processes (e.g., Baumeister, 1984; Lewis & Linder, 1997). Thus, this theory can provide an explanatory account for performance failure in the later stage.

In ACT-R, like the activation mechanism, productions have their own utility values. Based on these utility values, one production can be preferred and be selected over another. Also, the utilities can be learned from experience. If we let the expected utility as  $U_j$ , the probability of choosing a production  $i$  is:

$$\text{Probability}(i) = \frac{e^{U_i/\sqrt{2s}}}{\sum_j e^{U_j/\sqrt{2s}}} \quad \text{Equation 3.}$$

In the denominator of Equation 3 (conflict resolution equation), the summation indicates the sum of all productions that can currently be fired. That is, their conditions are satisfied during the match. The  $s$  parameter controls the noise in the utilities and it is conventionally set to 1. This equation is the same as the

Boltzmann equation that serves as the selection mechanism—in this context, the parameter  $s$  indicates temperature. The utilities of productions can be dynamically adjusted in terms of the reward they receive. This is called the utility learning. Let  $U_i(n-1)$  is the utility of a production  $i$  after its  $n-1$ th application and  $R_i(n)$  is the reward the production receives for its nth application. The utility,  $U_i(n)$ , after its nth is:

$$U_i(n) = U_i(n-1) + \alpha[R_i(n) - U_i(n-1)] \quad \text{Equation 4.}$$

$U_i(n)$ : the value of an item  $i$  after its nth occurrence

$R_i(n)$ : the reinforcement of a reward or a penalty on the nth occurrence

$\alpha$ : the rate of learning,  $0 < \alpha < 1$

Equation 4 is the current equation that is used in ACT-R to calculate the utility value for each production. While the latest version of ACT-R uses the utility value based on Equation 4, the previous version of ACT-R used a simpler equation,  $U_i = P_i G - C_i + \epsilon$ , where  $P_i$  represents the estimated probability that the goal will be achieved if that production is chosen,  $G$  represents the value of the goal, and  $C_i$  represents the estimated cost of achieving the goal if that production is chosen. This utility equation is limited to learning from binary feedback—that is, whether a reward is received or not. This is not sufficient to represent the feedback from the environment, and, thus, the latest version of the ACT-R 6 architecture uses a new utility mechanism as shown in Equation 2, which is similar to the reinforcement learning of Rescorla and Wagner (1972).

Figure 4 shows the computational changes of the expected utility values of the three arbitrary production rules over trials. The productions are reaching their steady-state values. Differing utility values of the productions that control the selection and firing of those production may provide a mechanism representing degraded performance. Consequently, performance failure under stress in the later stage can be represented by the utility learning mechanism. Figure 5 shows an integrated understanding of performance response capacity change (i.e., increase or decrease in time to complete the task). However, little research has been conducted to represent performance degradation in procedural memory using the utility learning mechanism.

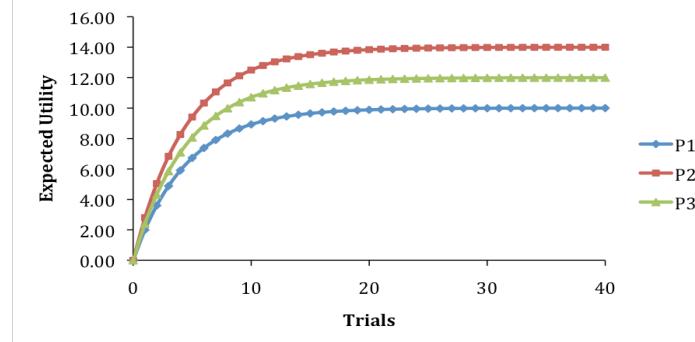


Figure 4. The expected values of the three arbitrary productions.

Beilock and Carr (2001) pointed out that the aforementioned theories have been seemingly considered to be mutually exclusive but should, in fact, be considered to be complimentary. This complimentary understanding is possible when we consider the three stages of performance change shown in Figure 2 and 5. That is, under the distraction theory, task skills reside in the early stage and rely on declarative memory item retrieval (e.g., foreign language learning), and under exploit monitoring theory, task skills reside in the later stages and rely on production rules.

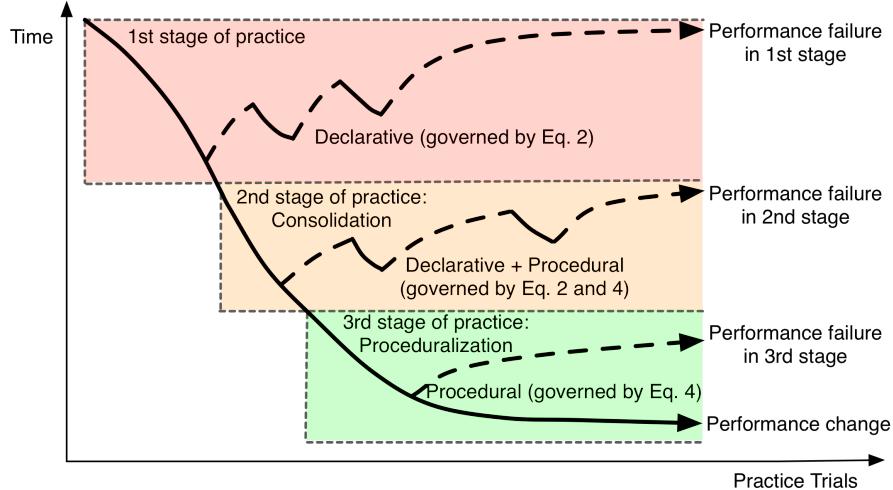


Figure 5. An integrated understanding of performance response capacity change.

## 4.2 Consideration of Interactive Behavior under Time Stress

Gray (2000) and Byrne (2001) have used the term embodied cognition to describe interactive behavior in specific contextually-constrained environments. Thus the interactive behavior of any operator is a function of the properties of their respective perceptual, motor, and cognitive capabilities in conjunction with the Cognition-Task-Artifact triad that is the framework for understanding such interactive behavior (Gray & Altmann, 2001). The *soft constraints hypothesis* assumes that interactive routines that consist of cognition, perception, and motor operations are selected to minimize the performance cost as measured in time (Gray, Sims, Fu, & Schoelles, 2006).

A counterpart proposal, the *minimum memory hypothesis*, suggests that people favor strategies to minimize their load on memory. Wilson (2002) argues that people tend to reduce cognitive workload by transferring such load wherever possible onto the environment itself. Cary and Carlson (1999) also support the notion that people tend to minimize working memory demands in problem-solving routines. Such notions however, do not account for performance costs that are sensitive to time.

The ubiquity of GUI type interfaces illustrates the preference that people possess a bias toward favoring perceptual-motor effort to decrease the use of their memory. Thus, a minimum memory strategy would take a longer time to complete the task. Interestingly, individuals chose this strategy in their task performance, even though memorization saves time and they have been instructed to complete the task as quickly as possible (Ballard, Hayhoe, Pook, & Rao, 1997). In terms of this minimum memory strategy, we can presume that people prefer to use *knowledge in-the-world* even though it takes more time to complete. In the meantime, Gray and his associates argue that a user would choose one set of interactive routines (i.e., a pattern of cognitive, perceptual, and motor operations) over another as a cost-benefit tradeoff, serving as the soft constraints that are only sensitive to the expected utility in time (Gray & Fu, 2004; Gray, Sims, Fu, & Schoelles, 2006).

What if the two strategies of interaction-intensive and memory-intensive change as to the progression of the performance response change (i.e., from novice to expert performance)? Unfortunately, as yet, we little know of any formal relationship between the interactive behavior in a task environment and time pressure.

Particularly, we have to identify what specific cognitive mechanisms are involved in responses under time stress.

### 4.3 Consideration of Working Memory Capacity

Wickens and Hollands (2000) have proposed that there are a number of ways human errors might occur under stress. These include interference to the aforesaid working memory capacity but also failure via interference to attention, decision-making processes, as well as long-term memory storage and access. In respect of working memory failures, to which the present proposal is most specifically directed, it is possible that under time stress (i) working memory might be less available for storing and integrating information, (ii) working memory interruptions mean that acquired knowledge may not be successfully retrieved; and/or (iii) working memory may be relocated to the time-related aspects of performance rather than the task per se. Or, the central executive is unwilling to wait for long term memory retrieval to occur, and instead executes simpler less memory intensive strategies. Or, or, a combination or subtle shift in the distribution of the use of these strategies occurs.

We have started to review existing information as to the methods of modeling time pressure in ACT-R (see Table 2). The study by Lerch, Gonzalez, and Lebiere (1999) is perhaps the first identified attempt to model time pressure in a dynamic task. In this study, time pressure was represented by modifying the rate at which the environment changed and compared the ACT-R time to that rate (see Lerch, Gonzalez, & Lebiere, 1999). This paper does not present the actual model code of this model. However, we suspect that this model's capability could be limited because no official timing module for ACT-R was available at that time in 1990s. Therefore, our present modeling begins with an effort to represent user performance under time pressure by exploring the predicted performance response change (e.g., accuracy and latency) based on the inter-relationship between the timing module proposed by Byrne (2006) and the  $W$  parameter to manipulate cognitive load in working memory (e.g., Lovett, Daily, & Reder, 2000). It is along this line of structure that our present efforts are progressing. Figure 6 shows an example of performance change in ACT-R. Different  $W$  parameter values indicate adjusting cognitive load in the model's working memory.

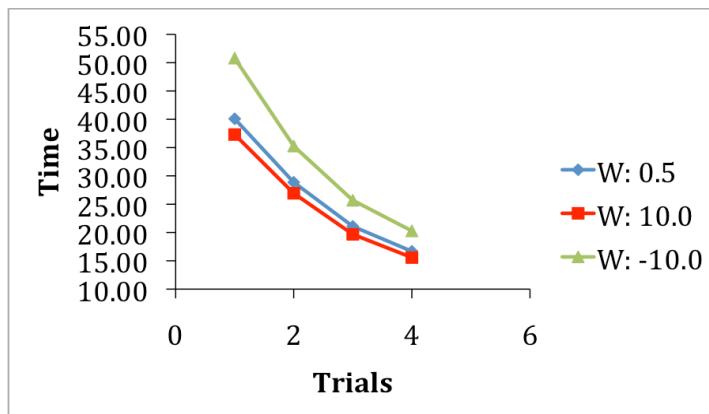


Figure 6. Performance change in ACT-R by adjusting working memory capacity.

## 5 Summary for the Roadmap

As mentioned earlier, the objective of our research project is to: (a) provide a formalized model of human performance under time pressure, (b) provide a cognitive mechanism-based account of failure under time

pressure, (c) develop a unified theory of cognition under stress, and (d) create an empirical study environment where we can compare the model performance against human performance data. Based on suggestions by our ongoing work<sup>1</sup> (e.g., Kim & Hancock, 2010) and by the technical basis above, we specify the following tasks and goals as a roadmap for research studies in this area.

## 5.1 Roadmap 1: Create an Advanced Study Paradigm for Modeling

A study environment with which a cognitive model and human subjects can directly interact provides more precise comparison. This effort leads to building a ground where we can implement a cognitive model with accuracy and sensitivity with regard to human performance, providing more advanced prediction. Unfortunately, a cognitive model usually fails to connect to the real task environment—the model always resides in the head. That is, cognitive models—human behavior representations—are generally limited to accessing an external task environment because it is difficult to connect a model user to the task environment with which a human user interacts (Ritter, Baxter, Jones, & Young, 2000). Such connections are technically challenging. It also should mimic limitations and capabilities of human performance. Ritter et al. (2000) note several advantages of embodying a cognitive model: (a) Easier access to a much broader range of tasks, and (b) Easier to expand the model.

For a model to interact with a real task, it needs to have visual perception and motor action capabilities. Researchers have studied how to embody a computational cognitive model to interact with a simulated task environment. For example, the Argus system supports an embodied cognitive model to interact with a radar-like target classification task (Gray, 2002; Schoelles & Gray, 2001). In the Argus system, the model and the human subjects use the same interface. It is useful for the development of models including human cognition, human performance or AI agents to have access to real-world tasks, task environments, and interfaces.

We have been developing a task environment (shown in Figure 7) that has been purpose-developed to test a cognitive theory (e.g., the ACT-R theory). The task environment is a novel spreadsheet called Dismal. The Dismal<sup>2</sup> spreadsheet was implemented to gather and analyze behavioral data (Ritter & Wood, 2005). It is a part of the GNU Emacs distribution. Dismal extends the GNU Emacs editor using its extension language, Emacs Lisp.

This task environment provides the nature of cognition-demanding tasks for the experimental study, and the spreadsheet can be modified to support different types of inputs. It also provides a task with some ecological validity. Our spreadsheet task is done with a tool that allows us to examine two sets of knowledge and skills, that is, procedural or declarative, and cognitive or perceptual-motor skills. Research of text editing skills has provided important findings on human performance and information processing. For example, Card, Moran, and Newell (1983) studied how a user's skills would interact with computer-based systems focusing on text editing tasks. Singley and Anderson (1989) investigated the transfer of cognitive skills in text editing tasks by providing an in-depth theory of learning through the ACT\* architecture. In our study, as an extension of text editing tasks, a set of spreadsheet tasks will be examined to measure human performance under time pressure. In this study paradigm, keystrokes, mouse clicks, mouse movements, and task completion time can be recorded in milliseconds by the Recording User Input (RUI) system (Kukreja, Stevenson, & Ritter, 2006). The RUI data provides recording of participants' keystrokes, mouse button clicks (pressed and released), and mouse movements (e.g., xy coordinates of

<sup>1</sup> Sponsored by Army Research Office under the short term innovative research (STIR)

<sup>2</sup> <http://acs.ist.psu.edu/dismal/dismal.html>

mouse locations in pixels). The task environment is relevant here because human participants can interact with the Dismal spreadsheet and the ACT-R model can also interact with the task environment, providing a better comparison between the model and data and a better development platform of cognitive theories.

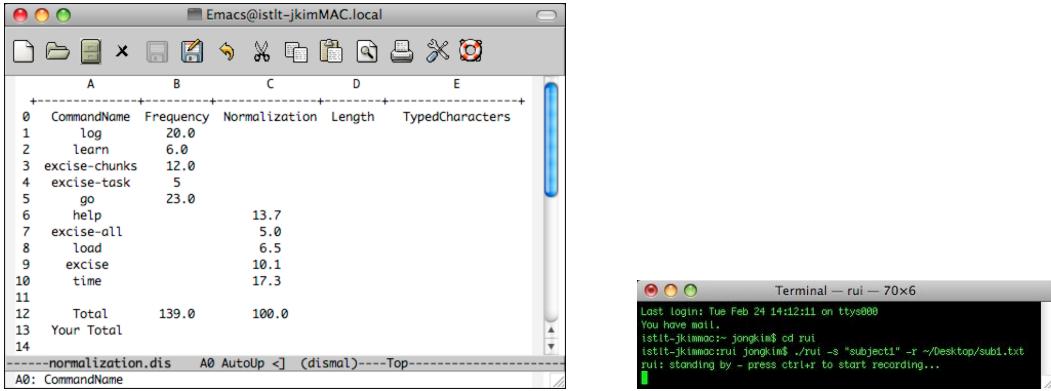


Figure 7. The task environment for exploration of human performance in a controlled laboratory setting.  
Dismal is shown on the left and RUI is on the right.

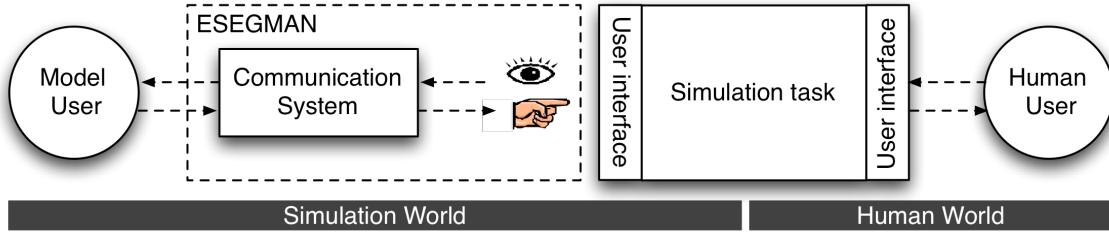
## 5.2 Roadmap 2: Develop Cognitive Models

In this study environment, it is necessary to develop and test a series of cognitive models to represent how performance capacity changes in terms of various task subskills (cognitive, perceptual, motor task subskills) under time pressure. One of the ACT-R's limitations is that the ACT-R model does not afford any difference on performance capacity changes in terms of different task subskills (i.e., the aforementioned task skill ontology). That is, performance capacity change of typing letters is different from the one of memorizing foreign vocabulary.

Particularly, it is necessary to provide theoretical accounts based on the ACT-R architecture of how interactive behavior is moderated under time pressure and how an individual chooses a strategy to complete a task (i.e., interaction-intensive vs. memory-intensive strategy). Furthermore, we need to examine how these strategies are affected by progression of the three stage of performance change (i.e., beginner vs. skilled behavior) under time pressure.

## 5.3 Roadmap 3: Embody the Cognitive Model

Previously, we initiated a process, named ESEGMAN (Emacs SubstratE: Gates toward MAN-made world), to connect a cognitive model to the real world task (Kim, Ritter, & Koubek, 2006). ESEGMAN is layered on the operation of Emacs and allows a model to see and to touch a task environment. Figure 8 depicts how ESEGMAN functions with a model user and a human user. An Emacs shell process is spawned, and the model's architecture is loaded within that process. A shell is started in Emacs to invoke OpenMCL that is a Lisp implementation. Then, ACT-R 6 is loaded into OpenMCL. An ACT-R model can send commands to the ESEGMAN, such as to move a mouse, to type a letter, or to be passed the contents of the Dismal spreadsheet screen as through a fovea.



*Figure 8.* A cognitive model with ESEGMAN interacting with a task environment that a human user interacts with.

In Emacs, there is a set of functions to take the output from the shell and insert output into the associated buffer. This approach allows a natural place for ESEGMAN to inspect what is sent, and if a command is sent, to execute it. If the command is to type a letter or to execute a keystroke command, this can be done directly using the extension language of Emacs Lisp. If the command moves the mouse, a model mouse pointer is moved, and shown in the mode line of the buffer being used by the model. If the command executes a mouse action, the corresponding process as for keystrokes is executed.

When the model wants to look at the screen, ESEGMAN takes the current fovea location and sets up a data structure of what can be seen, and send this back to the ACT-R model. ESEGMAN can create a file, or it can pass back through the process to an associated buffer. This may be done by creating a file, but we prefer to start with a simpler approach. ACT-R, after sending the fovea a *look command*, has a read that collects the incoming information and puts it into ACT-R's visual iconic memory.

Our current proposal includes completion of this ESEGMAN. The completed version will provide a cognitive plausible link between a real world task and a model to support a strong comparison between a model performance and a human performance in a laboratory setting. It will be also reusable as both a theory and a piece of software.

#### 5.4 Further Challenge: Identify the Three Stages

It remains an open question as to how we can identify what stage an individual is while performing the task. Theoretically, it is clear where an individual's stage is, but it is challenging to provide a data set that unequivocally demonstrates this identification. Further work with models and data may help elucidate using a model-based approach for tasks where models are available. It might also be possible to use an EEG system to identify performance changes in the three stages. There is little in terms of previous, existing work concerning the identification of an individual's stage while performing the task in terms of the three stages of performance change. It is valuable to explore this avenue of progress. The data will be useful for an understanding of how an individual assimilate skills by transitioning across stages and will directly inform our model of stress disruption (e.g., stress may prevent stage transition).

## References

- Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review*, 89(4), 369-406.
- Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University.
- Anderson, J. R. (1987). Skill acquisition: Compilation of weak-method problem solutions. *Psychological Review*, 94(2), 192-210.
- Anderson, J. R. (1993). *Rules of the mind*. Hillsdale, NJ: Lawrence Erlbaum.
- Anderson, J. R. (2007a). *How can the human mind occur in the physical universe?* New York, NY: Oxford University Press.
- Anderson, J. R. (2007b). Using brain imaging to guide the development of a cognitive architecture. In W. D. Gray (Ed.), *Integrated Models of Cognitive Systems* (pp. 49-62). New York, NY: Oxford University Press.
- Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of mind. *Psychological Review*, 111(4), 1036-1060.
- Anderson, J. R., Fincham, J. M., & Douglass, S. (1999). Practice and retention: A unifying analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25(5), 1120-1136.
- Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought*. Mahwah, NJ: Lawrence Erlbaum.
- Ballard, D. H., Hayhoe, M. M., Pook, P. K., & Rao, R. P. N. (1997). Deictic codes for the embodiment of cognition. *Behavioral and Brain Sciences*, 20, 723-767.
- Baumeister, R. F. (1984). Choking under pressure: Self-consciousness and paradoxical effects of incentives on skillful performance. *Journal of Personality and Social Psychology*, 46(3), 610-620.
- Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology: General*, 130(4), 701-725.
- Belavkin, R. V. (2001). Modeling the inverted-U effect with ACT-R. In E. M. Altmann, A. Cleeremans, C. D. Schunn & W. D. Gray (Eds.), *Proceedings of the 4th International Conference on Cognitive Modeling* (pp. 275-276). Mahwah, NJ: Erlbaum.
- Block, R. A., Hancock, P. A., & Zakay, D. (in submission). Cognitive load affects duration judgments: A meta-analytic review.
- Byrne, M. (2006). An ACT-R timing module based on the attentional gate model. In *ACT-R Workshop Proceedings*. Pittsburgh, PA: CMU.
- Byrne, M. D. (2001). ACT-R/PM and menu selection: Applying a cognitive architecture to HCI. *International Journal of Human-Computer Studies*, 55(1), 41-84.
- Card, S. K., English, W. K., & Burr, B. J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics*, 21(8), 601-613.
- Card, S. K., Moran, T. P., & Newell, A. (1983). *The psychology of human-computer interaction*. Hillsdale, NJ: Lawrence Erlbaum.
- Cary, M., & Carlson, R. A. (1999). External support and the development of problem-solving routines. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25(4), 1053-1070.
- Delaney, P. F., Reder, L. M., Staszewski, J. J., & Ritter, F. E. (1998). The strategy-specific nature of improvement: The power law applies by strategy within task. *Psychological Science*, 9(1), 1-7.
- Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review*, 66(3), 183-201.
- Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 243-285). New York: Academic Press.
- Gray, W. D. (2000). The nature and processing of errors in interactive behavior. *Cognitive Science*, 24(2), 205-248.

- Gray, W. D. (2002). Simulated task environments: The role of high-fidelity simulations, scaled worlds, synthetic environments, and microworlds in basic and applied cognitive research. *Cognitive Science Quarterly*, 2(2), 205-227.
- Gray, W. D. (2008). Cognitive architecture: Choreographing the dance of mental operations with the task environment. *Human Factors*, 50(3), 497-505.
- Gray, W. D., & Altmann, E. M. (2001). Cognitive modeling and human-computer interaction. In W. Karwowski (Ed.), *International encyclopedia of ergonomics and human factors* (Vol. 1, pp. 387-391). New York: Taylor & Francis.
- Gray, W. D., & Fu, W.-T. (2004). Soft constraints in interactive behavior: the case of ignoring perfect knowledge in-the-world for imperfect knowledge in-the-head. *Cognitive Science*, 28, 359-382.
- Gray, W. D., Sims, C. R., Fu, W., & Schoelles, M. J. (2006). The soft constraints hypothesis: A rational analysis approach to resource allocation for interactive behavior. *Psychological Review*, 113(3), 461-482.
- Gunzelmann, G., Gross, J. B., Gluck, K. A., & Dinges, D. F. (2009). Sleep deprivation and sustained attention performance: Integrating mathematical and cognitive modeling. *Cognitive Science*, 33(5), 880-910.
- Hancock, P. A. (1993). Body temperature influence on time perception. *Journal of General Psychology*, 120(3), 197-215.
- Hancock, P. A., & Rausch, R. (2010). The effects of sex, age, and interval duration on the perception of time. *Acta Psychologica*, 133, 170-179.
- Hancock, P. A., & Szalma, J. L. (Eds.). (2008). *Performance under stress*. Aldershot, England: Ashgate Publishing.
- Hancock, P. A., & Warm, J. S. (1989). A dynamic model of stress and sustained attention. *Human Factors*, 31(5), 519-537.
- Jongman, G. M. G. (1998). How to fatigue ACT-R? In *Proceedings of 2nd European Conference on Cognitive Modeling* (pp. 52-57). Nottingham, UK: Nottingham University Press.
- Kim, J. W., & Hancock, P. A. (2010). Modeling operator performance under stress and fatigue: What can a cognitive architectural model tell us? In *Proceedings of Applied Human Factors and Ergonomics Conference*. Miami, FL.
- Kim, J. W., Ritter, F. E., & Koubek, R. J. (2006). ESEGMAN: A substrate for ACT-R architecture and an Emacs Lisp application. In *Proceedings of the 7th International Conference on Cognitive Modeling* (pp. 375-376). Trieste, Italy.
- Kukreja, U., Stevenson, W. E., & Ritter, F. E. (2006). RUI: Recording user input from interfaces under Window and Mac OS X. *Behavior Research Methods*, 38(4), 656-659.
- Lebiere, C., Biefeld, E., Archer, R., Archer, S., Allender, L. E., & Kelley, T. D. (2002). IMPRINT/ACT-R: Integration of a task network modeling architecture with a cognitive architecture and its application to human error modeling. In *Proceedings of the Advanced Technologies Simulation Conference* (pp. 13-18). San Diego, CA.
- Lerch, F. J., Gonzalez, C., & Lebiere, C. (1999). Learning under high cognitive workload. In *Proceedings of the Twenty-first Conference of the Cognitive Science Society* (pp. 302-307). Mahwah, NJ: Erlbaum.
- Lewis, B. P., & Linder, D. E. (1997). Thinking about choking? Attentional process and paradoxical performance. *Personality and Social Psychology Bulletin*, 23, 937-944.
- Lovett, M. C., Daily, L. Z., & Reder, L. M. (2000). A source activation theory of working memory: Cross-talk prediction of performance in ACT-R. *Journal of Cognitive Systems Research*, 1, 99-118.
- Neves, D. M., & Anderson, J. R. (1981). Knowledge compilation: Mechanisms for the automatization of cognitive skills. In J. R. Anderson (Ed.), *Cognitive Skills and Their Acquisition* (pp. 57-84). Hillsdale, NJ: Lawrence Erlbaum.

- Newell, A. (1973). You can't play 20 questions with nature and win: Projective comments on the papers of this symposium. In W. G. Chase (Ed.), *Visual information processing* (pp. 283-308). New York: Academic Press.
- Newell, A. (1990). *Unified Theories of Cognition*. Cambridge, MA: Harvard University.
- Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive Skills and Their Acquisition* (pp. 1-55). Hillsdale, NJ: Lawrence Erlbaum.
- Pavlik, P. I., & Anderson, J. R. (2005). Practice and forgetting effects on vocabulary memory: An activation-based model of the spacing effect. *Cognitive Science*, 29, 559-586.
- Posner, M. I. (1973). *Cognition: An introduction*. Glenview, Illinois: Scott, Foresman and Company.
- Reason, J. (1997). *Managing the risks of organizational accidents*. Aldershot, UK: Ashgate.
- Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: variations in the effectiveness of reinforcement and nonreinforcement. In A. H. Black & W. F. Prokasy (Eds.), *Classical Conditioning II: Current Research and Theory*. New York: Appleton-Century-Crofts.
- Ritter, F. E., Baxter, G. D., Jones, G., & Young, R. M. (2000). Supporting cognitive models as users. *ACM Transactions on Computer-Human Interaction*, 7(2), 141-173.
- Ritter, F. E., Reifers, A. L., Klein, L. C., & Schoelles, M. J. (2007). Lessons from defining theories of stress. In W. D. Gray (Ed.), *Integrated models of cognitive systems* (pp. 254-262). New York, NY: Oxford University Press.
- Ritter, F. E., Schoelles, M., Klein, L. C., & Kase, S. E. (2007). Modeling the range of performance on the serial subtraction task. In R. L. Lewis, T. A. Polk & J. L. Laird (Eds.), *Proceedings of the 8th International Conference on Cognitive Modeling* (pp. 299-304). Oxford, UK: Taylor & Francis/Psychology Press.
- Ritter, F. E., & Schooler, L. J. (2001). The learning curve. In *International Encyclopedia of the Social and Behavioral Sciences* (pp. 8602-8605). Amsterdam: Pergamon.
- Ritter, F. E., & Wood, A. B. (2005). Dismal: A spreadsheet for sequential data analysis and HCI experimentation. *Behavior Research Methods*, 37(1), 71-81.
- Schoelles, M. J., & Gray, W. D. (2001). Argus: A suite of tools for research in complex cognition. *Behavior Research Methods, Instruments, & Computers*, 33(2), 130-140.
- Seibel, R. (1963). Discrimination reaction time for a 1,023-alternative task. *Journal of Experimental Psychology*, 66(3), 215-226.
- Singley, M. K., & Anderson, J. R. (1989). *The transfer of cognitive skill*. Cambridge, MA: Harvard University.
- Taatgen, N. A., van Rijn, H., & Anderson, J. R. (2007). An integrated theory of prospective time interval estimation: The role of cognition, attention, and learning. *Psychological Review*, 114(3), 577-598.
- VanLehn, K. (1996). Cognitive skill acquisition. *Annual Review of Psychology*, 47, 513-539.
- Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River, NJ: Prentice-Hall.
- Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, 9(4), 625-636.
- Wine, J. (1971). Test anxiety and direction of attention. *Psychological Bulletin*, 76(2), 92-104.
- Zakay, D., & Block, R. A. (1997). Temporal cognition. *Current Directions in Psychological Science*, 6(1), 12-16.